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ENHANCED WATER TREATMENT VIA CATALYST-INTEGRATED GLIDING ARC PLASMA TECHNOLOGY: A REVIEW

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Abstract. *The increasing prevalence of industrial pollutants, particularly synthetic dyes, in water bodies has necessitated the development of efficient and sustainable treatment methods. This review comprehensively examines the use of gliding arc plasma technology, coupled with various catalysts, for the degradation of persistent organic pollutants such as azo dyes, acid dyes, and other synthetic colorants. The synergistic effects of combining plasma with different catalysts are analyzed, highlighting their impact on degradation efficiency and reaction kinetics. Key findings from recent studies are summarized, focusing on the degradation rates, catalyst performance, and experimental conditions. The review also discusses the underlying mechanisms of plasma-catalyst interactions, offering insights into the role of different catalysts in enhancing pollutant breakdown. Furthermore, the article identifies current challenges and proposes future research directions to optimize gliding arc plasma technology for large-scale environmental applications. This work underscores the potential of plasma-assisted catalysis as a promising approach for water treatment, contributing to the advancement of sustainable and effective remediation technologies.*

Keywords: *Water treatment, non-thermal plasma, gliding arc plasma, catalysts, dyes, plasma-assisted catalysis.*

УЛУЧШЕННАЯ ОЧИСТКА ВОДЫ С ПОМОЩЬЮ ТЕХНОЛОГИИ СКОЛЬЗЯЩЕГО ДУГОВОГО РАЗРЯДА С ИНТЕГРИРОВАННЫМ КАТАЛИЗАТОРОМ: ОБЗОР

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Аннотация. *Увеличивающаяся распространенность промышленных загрязнителей, в частности синтетических красителей, в водоемах требует разработки эффективных и устойчивых методов очистки. В этом обзоре всесторонне рассматривается использование технологии скользящей дуговой плазмы в сочетании с различными катализаторами для деградации стойких органических загрязнителей, таких как азокрасители, кислотные красители и другие синтетические красители. Проанализированы синергетические эффекты комбинации плазмы с различными катализаторами, подчеркивающие их влияние на эффективность деградации и кинетику реакции. Ключевые результаты недавних исследований обобщены с акцентом на скорость деградации, производительность катализаторов и экспериментальные условия. Обзор также обсуждает основные механизмы взаимодействия плазмы и катализаторов, предоставляя информацию о роли различных катализаторов в улучшении разрушения загрязнителей. Кроме того, статья определяет текущие проблемы и предлагает направления для будущих исследований с целью оптимизации технологии скользящей дуговой плазмы для применения в крупных масштабах в области охраны окружающей среды. Это исследование подчеркивает потенциал катализируемого плазмой подхода как перспективного метода для очистки воды, способствуя развитию устойчивых и эффективных технологий ремедиации.*
Ключевые слова: *Очистка воды, низкотемпературная плазма, скользящая дуговая плазма, катализаторы, красители, катализ с участием плазмы.*

KATALIZATOR BILAN INTEGRATSIYALANGAN GLIDING ARC PLAZMA TEXNOLOGIYASI ORQALI YAXSHILANGAN SUV TOZALASH: TAHLILIY SHARH

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Annotatsiya. *Suv havzalarida sanoat ifloslantiruvchilari, xususan, sintetik bo‘yoqlarning keng tarqalishi samarali va barqaror tozalash usullarini ishlab chiqishni talab qilmoqda. Ushbu maqolada gliding arc plazma texnologiyasidan turli katalizatorlar bilan birgalikda foydalanishni, azo bo‘yoqlar, kislota bo‘yoqlari va boshqa sintetik rang beruvchi moddalarga o‘xshash barqaror organik ifloslantiruvchilarni parchalash uchun qo‘llanilishini har tomonlama o‘rganiladi. Plazma va turli katalizatorlarning kombinatsiyasining sinergik ta’siri tahlil qilinib, ularning parchalanish samaradorligi va reaksiya kinetikasiga ta’siri ko‘rsatib beriladi. So‘nggi tadqiqotlarning asosiy natijalari umumlashtirilib, asosan degradatsiya tezligi, katalizatorlarning samaradorligi va eksperimental sharoitlarga e’tibor qaratilgan. Maqolada plazma va katalizatorlar o‘zaro ta’sirining asosiy mexanizmlarini ham muhokama qilinadi va turli katalizatorlarning ifloslantiruvchi moddalarni parchalanishini kuchaytirishdagi rolini tushuntiradi. Shu –*

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ningdek, maqolada hozirgi muammolar aniqlanib, gliding arc plazma texnologiyasini keng miqyosda atrof-muhitga oid qo'llanmalar uchun optimallashtirishga qaratilgan kelajakdagi tadqiqot yo'nalishlari taklif etadi. Ushbu ish plazma yordamida katalizni suvni tozalash uchun istiqbolli yondashuv sifatida ko'rsatib, barqaror va samarali reabilitatsiya texnologiyalarini rivojlantirishga hissa qo'shadi.
Kalit so‘zlar: *Suvni tozalash, sovuq atmosferali plazma, gliding arc plazma, katalizatorlar, bo‘yoqlar, plazma yordamida kataliz.*

Introduction. The rapid depletion of natural water resources due to increasing global warming and a growing world population has intensified the need for effective wastewater treatment solutions. Urban development has intensified water pollution through industrial and agricultural waste, posing significant threats to human, animal, and aquatic life. Over 1 billion people worldwide lack access to clean drinking water, resulting in more than a million deaths annually due to diseases and chronic illnesses linked to polluted water. The textile dyeing industry is a major contributor to organic waste in water bodies, with the World Bank reporting that these industries account for 17–20% of global water pollution [1]. Most synthetic organic dyes are utilized in the textile and tannery industries for coloring products like clothing, carpets, bedding, leather goods, and soft furnishings. There are around 10,000 different textile dyes, with a global annual production exceeding 700,000 tons. The most significant dyes in the textile sector include azo, anthraquinone, and phthalocyanine dyes. Releasing dye-polluted water impacts its visual quality, reduces its ability to reoxygenate, and decreases light penetration. Additionally, dyes cause significant acute and chronic toxicities, harming both aquatic ecosystems and human health. The substantial impact of these pollutants on the environment and human health is a major concern, leading to increasingly stringent legislative demands globally [2]. This highlights the urgent need to adopt cleaner technologies to degrade dye molecules before they are released into the environment. Over the past century, numerous water decontamination techniques have been developed. Traditional methods like activated sludge treatment, adsorption, membrane separation, biological treatments, and chemical precipitation are commonly used in the industry. Generally, water treatment is a complex, multistage process that takes significant time. Emerging advanced oxidation processes (AOPs) offer innovative solutions for water decontamination. These advanced techniques include photocatalysis, ozonation, sonolysis, electrochemical treatments, non-thermal processes, and Fenton and photo-Fenton processes. Among these, non-thermal plasma technology is a new advanced oxidation technology for water treatment, which includes the effects of free radical oxidation, high energy electron radiation, ultraviolet light hydrolysis, and pyrolysis. In order to improve the energy efficiency in the plasma discharge processes, many efforts have been made to combine catalysts with discharge plasma technology. Some heterogeneous catalysts (e.g., activated carbon, zeolite, TiO_2) and homogeneous catalysts (e.g., Fe^{2+}/Fe^{3+}, etc.) have been used to enhance the removal of pollutants by discharge

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plasma. Non-thermal plasma is a highly promising technology for degrading hazardous pollutants in wastewater. Among the various types of plasma sources, gliding arc plasma has proven particularly effective in generating reactive species such as hydroxyl radicals (•OH), hydrogen peroxide (H_2O_2), and ozone (O_3), which are crucial for the oxidative degradation of organic pollutants in wastewater. Gliding arc plasma operates by generating plasma through gas discharges in different configurations, using various feed gases such as N_2, O_2, air, and noble gases [3]. The discharge can occur in bubbles or above thin liquid films, creating reactive species that penetrate the liquid phase and initiate degradation processes. These species transfer from the gas phase to the liquid, where they induce reactions that break down pollutants. Recent studies have shown that various operational factors significantly affect the effectiveness of Non-Thermal Plasma (NTP)-based processes. Incorporating a catalyst into the NTP reactor notably enhances process efficiency compared to NTP treatment alone [4]. Some researchers have investigated the synergistic effect of NTP combined with catalysts for removing diverse pollutants from aqueous solutions. However, identifying universally optimal conditions for all contaminants and catalyst types remains challenging. The integration of catalysts with gliding arc plasma systems can significantly enhance the degradation efficiency and mineralization of organic pollutants. Catalysts facilitate the generation of additional reactive species and improve reaction kinetics, thus reducing treatment time and increasing the percentage of degradation. The synergy between plasma and catalysts offers a robust approach to tackle complex wastewater contaminants, making it a promising technology for future applications [5].

Non-thermal plasma: gliding arc reactor. Plasma, frequently referred to as the fourth state of matter contains electrons, ions, and radicals. In nature, plasma can be observed in phenomena such as stellar structures and the northern lights. Plasmas are commonly categorized into thermal and nonthermal types. Thermal plasmas, also known as high-temperature plasmas, exhibit high energy densities and are highly efficient for rapid processing. These plasmas typically maintain high gas and electron temperatures, often approaching or achieving equilibrium states [6]. Gas molecules within thermal plasmas are predominantly or fully ionized. In contrast, nonthermal plasmas, referred to as low-temperature, cold, or non-equilibrium plasmas, are characterized by weak to partial ionization. Thermal plasmas can be operated with very high power, and the reaction process is also very fast since the voltage required to sustain them is very low. The main disadvantage of thermal plasma processes is their inherently thermal nature, which results in low chemical selectivity.

Nonthermal plasma is characterized by its notably higher electron temperatures compared to ions and neutrals. In nonthermal plasma, electron temperatures can range broadly from 10,000 to 100,000 Kelvin, which corresponds approximately to 1–10 electron volts (eV). In contrast, ions and neutral particles typically remain at lower temperatures, often around room temperature or several hundred Kelvin. This temperature disparity highlights the unique energetic distribution within non-thermal plasma, where electrons possess significantly higher kinetic energies than other

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particles present in the plasma environment. High-energy electron collisions with gas molecules in plasmas produce a wide variety of active species that can engage in chemical reactions. These active species include excited molecules and atoms, ions, radicals, and even new stable molecules [7].

and molecular species and breaking chemical bonds. During excitation, if a reactant enters an excited state, it can overcome the activation energy (E_A) and trigger the chemical reaction. Most chemical reactions have an E_A of less than 5 eV. To dissociate a molecule and produce a free

Table 1.

Summary some of the main chemical reactions occurring in plasmas.

Reaction type	Reaction	Description
Electron/Molecular reactions		
Excitations	$e^- + A_2 \rightarrow A_2^* + e^-$	An electron collides with a molecule, exciting it.
Dissociation	$e^- + A_2 \rightarrow 2A + e^-$	An electron collides with a molecule, breaking it into two atoms.
Attachment	$e^- + A_2 \rightarrow A^-_2$	An electron attaches to a molecule, forming a negative ion.
Dissociative Attachment	$e^- + A_2 \rightarrow A^- + A$	An electron attaches to a molecule, causing it to dissociate.
Ionization	$e^- + A_2 \rightarrow A^+_2 + 2e^-$	An electron collides with a molecule, ionizing it and releasing two electrons.
Dissociative Ionization	$e^- + A_2 \rightarrow A^+ + A + e^-$	An electron collides with a molecule, ionizing and dissociating it.
Recombination	$e^- + A^+_2 \rightarrow A_2$	An electron recombines with a molecular ion, neutralizing it.
Detachment	$e^- + A^-_2 \rightarrow A_2 + 2e^-$	An electron collides with a negative ion, detaching an electron and forming a neutral molecule.
Atomic/Molecular Reactions		
Penning Dissociation	$M + A_2 \rightarrow 2A + M$	An excited atom or molecule (M) collides with a molecule, causing it to dissociate.
Penning Ionization	$M^* + A_2 \rightarrow A^+_2 + M + e^-$	An excited atom or molecule (M*) ionizes a molecule upon collision.
Charge Transfer	$A^+ + B \rightarrow B^+ + A$	An ion transfers its charge to another atom or molecule.
Ion Recombination	$A^- + B^+ \rightarrow AB$	A negative ion recombines with a positive ion to form a molecule.
Neutral Recombination	$A + B + M \rightarrow AB + M$	Two atoms recombine to form a molecule, with a third body (M) assisting in energy transfer.
Decomposition Reactions		
Electronic	$e^- + AB \rightarrow A + B + e^-$	An electron collides with a molecule, breaking it into atoms.
Atomic	$A^* + B_2 \rightarrow AB + B$	An excited atom reacts with a molecule, forming a new molecule and an atom.
Synthesis Reactions		
Electronic	$e^- + A \rightarrow A^* + e^-$	An electron excites an atom, which then reacts with another atom to form a molecule.
	$A^* + B \rightarrow AB$	
Atomic	$A + B \rightarrow AB$	Two atoms directly react to form a molecule.

In this table: e − represents an electron; A and B represent atoms; A_2 and B_2 represent molecules. M is a temporary collision partner; ∗ indicates an excited or radical species; + and − indicate ions with their respective charge symbols.

The energy of electrons in NTP chemistry typically falls between 1 and 10 eV, making it well-suited for exciting atomic

radical, the energy provided must equal the bond strength that needs to be broken. The average bond dissociation energies of

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Table 2.

Energy associated with non-thermal plasma (NTP) activated particles, and examples of bond energies

Activated particles	Energy (eV)	Bond	Bond energy (eV)	Bond	Bond energy (eV)	Bond	Bond energy (eV)
Electrons	1–10	C–H	4.31	C–N	2.88	S–H	3.83
Ions	0 –2	C–C	3.61	C–P	2.74	S–O	5.43
Excited particles	0 –20	C–Cl	3.44	C=O	7.76	S–C	2.66
Photons	3–40	C–Br	2.87	N–O	1.83	S–P	2.40
		C–O	3.66	P–O	5.23	S=O	4.78

certain diatomic molecules, which indicate how difficult it is to break these bonds, generally range from 3 to 6 eV, as illustrated in Table 2.

Radicals generated by NTPs are highly reactive at low temperatures and useful for environmental applications. These applications include the degradation of volatile organic compounds and odors, reduction of gaseous pollutants like diesel emissions, enhancement of combustion, sterilization, and the treatment of drinking and wastewater.

Physical characteristics of plasma gliding arc. The Gliding Arc is a notable example of gliding discharge, first utilized for nitrogen-based fertilizer production in the early 20th century and later popularized for various chemical processes by Czernichowski in the 1990s. DC gliding arc discharge in air progresses through three distinct stages: gas breakdown, equilibrium plasma, and non-equilibrium plasma (as shown in Fig. 1). The first stage, gas breakdown, is initiated by a high-voltage power supply. This power supply creates a strong electric field that concentrates at the narrowest point between the two electrodes. This intense electric field triggers gas breakdown, leading to plasma formation at the narrowest point between two electrodes [8].

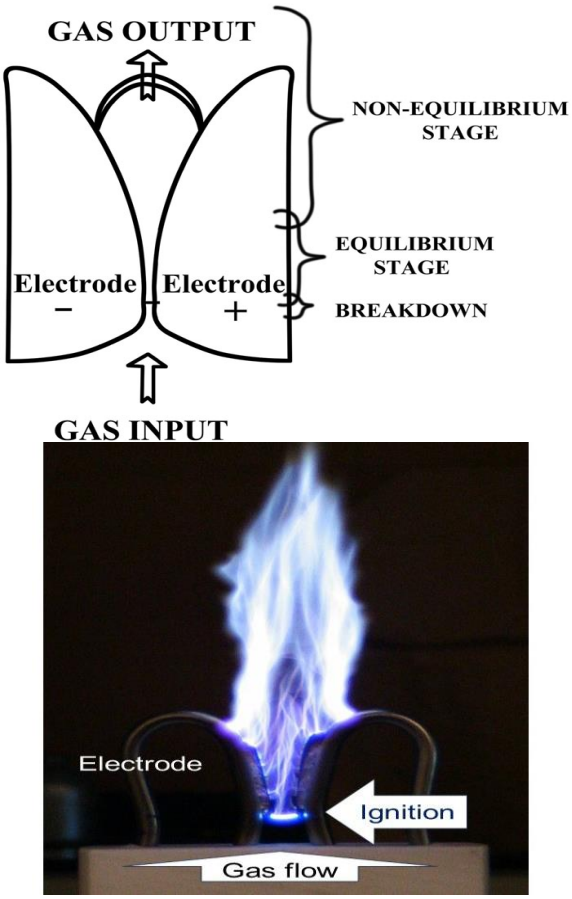

Figure 1. The schematic view of gliding arc discharge and a photograph of gliding arc discharge.

After the arc is ignited, the plasma enters an equilibrium stage where the gliding arc velocity matches the gas flow speed. This stage is characterized by high current and low voltage. Thermal ionization of

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neutral gas produces electrons, ions, and excited species. The temperatures of electrons, ions, and neutral particles are nearly equal. As the arc diffuses, the current decreases, but the energy consumed per unit length of the arc column remains constant, leading to an increase in voltage. When the arc length reaches a critical value, the equilibrium plasma transitions into a non-equilibrium plasma. During this transformation, the gliding arc exhibits both equilibrium and non-equilibrium properties, providing significant energy for practical applications. As the arc length further increases, heat diffusion loss from the plasma rises, preventing the maintenance of thermodynamic equilibrium [9]. Despite the constant electrical energy from the power source and rapidly decreasing gas temperature, plasma conductivity remains high due to electron avalanche effects and a high ionization rate (see Fig 2). In this stage, plasma parameters resemble those of non-equilibrium microwave plasma, characterized by high density and low temperature, which are ideal for plasma chemical processes. The electron vibration temperature reaches 3000 – 5000 K, facilitating chemical reactions.

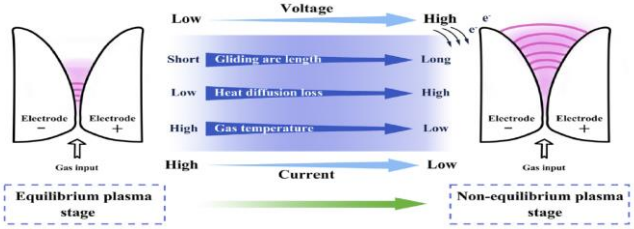

Figure 2. Schematic diagram of the physical characteristics of gliding arc discharge plasma [9].

After this rapid transformation, the arc achieves a non-equilibrium plasma state, where the electron temperature is significantly higher than the ion and neutral particle temperatures. The unit heat loss in this phase is about one-third of that in the equilibrium phase. The non-equilibrium plasma parameters are similar to those of microwave plasma at medium pressure (30–200 Torr), with an electron temperature of 1 eV and a gas temperature of 1500–3000 K. In this stage, 75%–80% of the gliding arc power is dissipated, and most of the input energy is used to generate high-energy electrons and reactive species, promoting efficient and selective non-equilibrium chemical reactions. In the non–equilibrium stage, the electron temperature is usually higher than 1 eV (1 eV = 11,605 K) and the gas temperature is generally below 3000 K. The non–equilibrium stage exhibits a strong chemical effect. Owing to the high electron temperature, many ions, electrons, and radicals are efficiently produced in the gliding arc. During the equilibrium-to-non-equilibrium transition, the gas temperature of the gliding arc decreases rapidly. This transition represent a shift from predominantly thermal effects to chemical effects. The gliding arc can be adjusted at different stages to accommodate various circumstances [10].

Chemical characteristics of gliding arc plasma. NTP generates a variety of reactive oxygen species such as hydroxyl radicals (OH), superoxide anion (O_2^-), hydrogen peroxide (H_2O_2), atomic oxygen (O), ozone (O_3), and singlet oxygen ($^1O_2$) (see Fig 3). It also produces reactive nitrogen species including nitric oxide (NO), nitrogen dioxide (NO_2), dinitrogen pentoxide (N_2O_5), and atomic nitrogen (N). Some of these species, such as OH radicals, O, NO, N, and $^1O_2$, are short-lived. The formation of reactive oxygen and nitrogen species is

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initiated by collisions between high-energy electrons and neutral molecules, resulting in the generation of primary reactive species. These primary reactive species include electrons (e^-), ionized neutrals and gases (M^+), excited neutrals and gases (M^*), N, O, atomic H, NO, and O_2^{*-}. These species are highly reactive but have very short lifetimes, typically in the microsecond range. For example, the lifetimes of OH radicals, NO, and O_2^{*-} are approximately 2.7 μs, 1.2 μs, and 1.3μs,respectively [11].

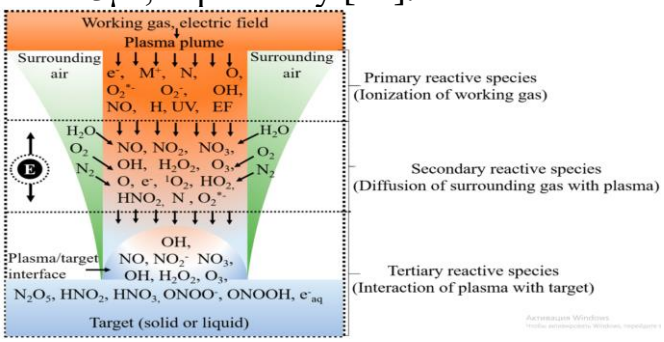

Figure 3. Schematic diagram of RONS formation within the discharge region, gas region, plasma/target interface, and inside the target.

Primary reactive species can undergo radiative decay or react with other species, leading to the formation of secondary reactive species such as H_2O_2, NO_2, NO_3, and O_3 in the ambient environment. When these secondary reactive species dissolve in the liquid phase, they form tertiary reactive species like H_2O_2, NO_2^-, and NO_3^-. Long-lived reactive species such as O_3, H_2O_2, NO_3^-, and NO_2^- can persist from milliseconds to several days and are soluble in water, where NO_2 and NO_3 rapidly convert to NO_2^- and NO_3^-. The dissolution of reactive species in the liquid phase can decrease the pH of the solution by up to 2 units, depending on factors such as the plasma source, working gas, power source, treatment duration, and sample volume. The chemistry of reactive oxygen and reactive nitrogen species formation varies depending on whether the target is in a dry or aqueous state [12]. NTP effectively generates various ROS and RNS through high-energy collisions, leading to the formation of primary, secondary, and tertiary reactive species. These species play crucial roles in applications like water purification, where they interact to degrade pollutants and reduce pH levels, enhancing the overall treatment process. Understanding the dynamics of these species is essential for optimizing the efficiency of NTP in environmental applications.

Gliding arc plasma with catalysts in degradation of pollutants in water. NPT technologies have been proven to be an emerging alternative for water pollutants treatment. NTP technology is widely used for different applications especially for the degradation of pollutants from wastewater. It is well known that the NTP process could produce active species such as O_3, H_2O_2 ·OH, ·O, which play a key role in the oxidative degradation of pollutants. However, some disadvantages of NTP "alone" in the degradation of organic contaminants are mainly linked to the formation of unwanted by-products that can limit its industrial applications. To overcome these limitations, an interesting strategy, consisting of the combination of NTP and heterogeneous catalysis, has been proposed to enhance pollutant degradation efficiency and, simultaneously, reduce the formation of reaction by-products. The effect of NTP combined with catalysts enhances the generation of different types of active species (such as hydroxyls) and the activity and stability of photocatalytic materials.

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These studies collectively highlight the potential of combining gliding arc discharge plasma with various catalysts for efficiently degrading organic pollutants in aqueous solutions. One study by Saïm et al. [13] developed a new method using gliding arc discharge (GAD) was developed to treat pollutant liquids. To speed up the process, researchers incorporated a thin layer of titanium dioxide deposited inside the GAD reactor. This "GAD/TiO_2" system effectively degraded an anthraquinonic dye (AG25) in water, significantly outperforming GAD alone. Analysis suggests the process breaks down the dye molecule, potentially with intermediate products attaching to the TiO_2 surface. This environmentally friendly method offers promise for scalable treatment of organic pollutants in liquids. Notably, After 180 minutes of treatment, AG25 dye degradation reached 59% with GAD-plate and 85% with GAD-plate-TiO_2. These results suggest that the presence of TiO_2 photocatalyst enhances the plasma chemical treatment, likely due to the additional OH radicals generated from both the plasma and TiO_2 particles. Similarly, another study by Tarkwa and colleagues [14] investigated the degradation of Orange G (OG) dye in aqueous solutions using laterite soil as a catalyst combined with gliding arc plasma treatment. The laterite soil, containing minerals like Al_2O_3, Fe_2O_3, and TiO_2, was calcined at 400°C and used at a concentration of 3 $g \cdot L^{-1}$. Experimental conditions involved a 500 mL gliding arc plasma reactor with pH adjusted between 3 and 10. Results demonstrated that while gliding arc plasma alone achieved a modest 17% degradation of OG, integration with laterite soil significantly enhanced degradation efficiency to nearly 100% within 60 minutes. Comparative experiments with P25 TiO_2 and Fe_2O_3 alone achieved 56% and 68% degradation, respectively, whereas a combined TiO_2/Fe_2O_3 system reached 75%. This research highlighted the synergistic effect of plasma activation and heterogeneous catalysis by laterite soil, showcasing its potential as a cost-effective and efficient method for treating dye-contaminated wastewater. The proposed mechanism involved hydroxyl radical (·OH) generation from plasma and photocatalytic processes facilitated by the mineral components of the laterite soil, emphasizing its stability and efficacy over multiple cycles. Additionally, in this study, an N-doped TiO_2/SiO_2 composite photocatalyst was synthesized by Suzie et al. [15]. The catalyst was evaluated for its effectiveness in degrading various dyes (Rhodamine 6G, Floxina B) and antibiotics (Ceftriaxone, Ampicillin) in aqueous media under both sunlight and non-thermal plasma irradiation. The study explores the synergistic effects of using gliding arc plasma (GAP) in conjunction with an N–TiO_2/SiO_2 composite catalyst for the degradation of pollutants. The combined approach leverages the strengths of both plasma treatment and photocatalysis, resulting in significantly enhanced degradation efficiencies. N–TiO_2/SiO_2 composite, when exposed to plasma, experiences an increase in surface activity due to the interaction with the reactive species produced by the plasma. This leads to more efficient electron-hole pair generation on the catalyst's surface. The presence of plasma helps to sustain the separation of electron-hole pairs generated in the N–TiO_2/SiO_2 composite. This reduces recombination rates and allows for more effective utilization of the charge carriers in

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degrading pollutants. The catalyst's surface properties facilitate the adsorption of pollutant molecules, bringing them into proximity to the reactive sites. Plasma-generated species further activate the catalyst surface, enhancing its adsorption capacity. The simultaneous presence of plasma-generated radicals and photocatalytic activity ensures that pollutants are attacked by multiple reactive species, leading to higher degradation rates. For example, the degradation efficiency of R6G was 52% with the combined approach, compared to only 12% with plasma alone and 10% under sunlight with the catalyst alone. The N–TiO_2/SiO_2 composite demonstrated consistent performance over multiple cycles, indicating that the plasma treatment not only enhances degradation efficiency but also helps maintain the catalyst's activity over prolonged use.

Moreover, the degradation of Acid Orange 7 (AO7) using a plasma-catalytic process was studied by Chang et al. [16] using a non-thermal gliding arc technique coupled with P25 TiO_2. Experiments optimized the amount of photocatalyst, showing maximum decolorization and degradation at a 0.5 $g \cdot L^{-1}$ TiO_2 concentration. At this optimum concentration, the dye (180 μM) was completely decolorized within 75 minutes of plasma/TiO_2 treatment, and 92.5% removal of initial chemical oxygen demand (COD) was achieved after 125 minutes. The degradation followed pseudo-first-order reaction kinetics. The primary intermediates of AO7 degradation included benzenesulfonic acid, hydroquinone, and various ring cleavage products. The study confirmed the effectiveness of combining gliding arc discharge plasma with TiO_2 photocatalysis for enhanced degradation of AO7. The plasma generated reactive species like hydroxyl radicals and UV radiation, which photoactivated TiO_2, enhancing oxidation and reduction reactions. The combined plasma and TiO_2 treatment showed higher degradation rates and COD reduction compared to plasma alone. 0.5 $g \cdot L^{-1}$ TiO_2 provided the best results, with complete decolorization and significant COD reduction within a shorter time frame. The presence of TiO_2 altered the degradation pathway of AO7 compared to plasma treatment alone. It facilitated the breakdown of AO7 into intermediate products such as benzenesulfonic acid, hydroquinone, and others, leading to more complete mineralization. This study by Djowe et al. [17] investigated the discoloration of Thiazol Yellow dye (TY) using a GAP process combined with Degussa P25 TiO_2 as a photocatalyst. The interaction between non-thermal plasma and the aqueous medium generates active species like NO• and HO• radicals, which contribute to the dye degradation. Discoloration experiments were conducted in a GAP batch reactor with 450 mL of Thiazol Yellow solutions at concentrations of 25, 50, and 100 $mg \cdot L^{-1}$. The solution was placed 50 mm from the electrode tips and stirred magnetically. Humid air at a flow rate of 800 L/h was used as the feed gas. The initial pH was set to 3.0, 5.5, or 9.0 using 1.0 M H_2SO_4 or 1.0 M NaOH. Solutions were exposed to plasma for 10, 20, 40, and 60 minutes, followed by UV-Vis spectrophotometry analysis at 402 nm. TiO_2 catalyst concentrations ranged from 0 to 6 $g \cdot L^{-1}$ in 50 $mg \cdot L^{-1}$ dye solutions, with a 30-minute dark adsorption period before plasma exposure. Higher initial dye concentrations led to higher discoloration rates, with maximum

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percentages of 36%, 38%, and 40% for 25, 50, and 100 mg·L^{-1} solutions, respectively, after 60 minutes without a catalyst. The pH of the solution decreased due to acidifying species formed during the process. The optimal pH for discoloration was 5.5. Conductivity changes were not influenced by dye concentration, suggesting a radical mechanism for dye degradation. Adding TiO_2 enhanced the discoloration rate, achieving a maximum of 70% at 2 g·L^{-1} TiO_2 for a 50 mg·L^{-1} dye solution after 60 minutes. Higher TiO_2 concentrations resulted in lower abatement rates due to aggregation effects. Combining the GAP process with TiO_2 catalyst effectively discolored Thiazol Yellow dye in wastewater. For a 50 mg·L^{-1} dye solution, discoloration increased from 38% with GAP alone to 70% with 2 g·L^{-1} TiO_2. This study demonstrates the potential of the GAP process combined with photocatalysis for efficient color removal in industrial wastewater. Another study by Du et al. [18] investigated the use of gliding arc discharge plasma (GAD) combined with zerovalent iron (ZVI) as Fenton catalyst for the degradation and discoloration of textile dyes (Alphazurine A, Acid Orange II (AOII), and Acid Anthraquinone Blue (AAB)) and their mixture. GAD generates reactive species like OH, NO, and H_2O_2, suitable for Fenton reactions in acidic conditions facilitated by ZVI. The research explores the efficiency of discoloration and degradation through UV-Vis analyses and chemical oxygen demand (COD) measurements. The experiments utilized a GAD reactor with stainless steel electrodes and a water-cooled glass vessel. Dye solutions were prepared with concentrations of 500 mg·L^{-1} for individual dyes and their mixture. ZVI (5 g·L^{-1}) was added to the dye solutions 24 hours prior to treatment to facilitate Fenton reactions. Treatments were conducted for durations ranging from 0 to 100 minutes under controlled conditions of gas flow (0.8 m^3/h) and solution feeding rate (60 ml/min). The study found that combining GAD with zerovalent iron (ZVI) facilitated Fenton reactions due to the acidic conditions and presence of H_2O_2 generated by GAD. This environment promoted the production of Fe^{2+} ions from ZVI, essential for generating OH• radicals. When treating mixed dyes, the addition of ZVI significantly improved discoloration rates, achieving 94.94% after 70 minutes. Moreover, ZVI enhanced degradation efficiency, with a kinetic constant of 0.0101 min^{-1} compared to 0.0019 min^{-1} without ZVI, demonstrating synergistic effects in dye breakdown and overall treatment efficiency enhancement. The study by Ghezzar et al. [19] investigated the effectiveness of coupling non-thermal glide arc plasma with TiO_2 catalyst in aqueous solutions for the depollution of organic dyes, specifically targeting the anthraquinonic dye Acid Green 25 (AG 25). The research aimed to improve treatment efficiency and generalize the approach to other pollutants. The study focused on optimizing several parameters, including the quantity of the catalyst, pH of the solution, nature of the substance, temperature, and compounds present in the solution. 2 g·L^{-1} of TiO_2 provided the best results, achieving complete decolorization within 15 minutes and 84% degradation within 1 hour. Higher concentrations resulted in reduced efficiency due to particle aggregation and light screening effects. The presence of TiO_2 significantly enhanced both decolorization and degradation rates compared to plasma

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treatment alone. The combined plasma-TiO_2 method proved to be a rapid and cost-effective approach for removing organic pollutants from aqueous solutions. The presence of TiO_2 significantly accelerated the decolorization of AG 25. While complete decolourization took 180 minutes with plasma alone, it was achieved in just 15

Table 3.

Summary of studies on gliding arc discharge plasma and catalysts for pollutant degradation

Target	Catalysts	Experimental Conditions	Results				Reaction time	Ref
			Gliding arc alone		Gliding arc with catalysts			
			Discol	Degrad	Discol	Degrad		
Orange G (OG) dye	Laterite Soil (Al_2O_3, Fe_2O_3, TiO_2)	Gliding arc plasma reactor; 500 mL OG solution; pH adjusted to 3–10; 3 g L−1 catalyst load;	17.4%	17	92.3%	Almost 100	60 min	[14]
Orange G	P25 TiO_2	Gliding arc plasma reactor; 500 mL OG solution; unspecified pH; 0.16 g L−1 P25 TiO2 load	17.4%	17	89.3%	56%	60 min	[14]
Orange G	TiO_2/Fe_2O_3	Gliding arc plasma reactor; 500 mL OG solution; unspecified pH; TiO2/Fe2O3 load equivalent to laterite content	17.4%	17	94.7%	75	60 min	[14]
Acid Green 25	TiO_2	80 mM (AG25 - Acid Green 25)	60% (60 min)	59%	94% (60 min)	85%	180 min	[13]
Rhodamine 6G	N–TiO_2@SiO_2	N–TiO2@SiO2 composite: 1 g/L, Rhodamine 6G (R6G) 10 mg/L	---	12	---	52	60 minutes.	[15]
Floxina B	N–TiO2@SiO2	N–TiO2@SiO2 composite: 1 g/L, Floxina B (FLB) 10 mg/L	---	22	---	72	60 minutes.	[15]
Acid Orange 7 (AO7)	Titanium Dioxide (TiO2)	180 µM Acid orange, Feeding Gas Compressed air, 0.5 g L−1 TiO2 catalyst load;	---	58.9	80.2%	100.0	75 min	[16]
Thiazol Yellow dye (TY)	P25 TiO2	50 mg/L dye solution, 2 g/L TiO2.	38%	---	70%	---	60 min	[17]
Alphazurine A (AA)	ZVI Zerovalent Iron (Fe^0)	Alphazurine A (AA) 500 mg/L Zerovalent Iron (Fe^0) 5 g	96.55	---	96.55	20.4	100 min	[18]
Acid Orange II (AOII)	ZVI Zerovalent Iron (Fe0)	Acid Orange II (AOII) 500 mg/L Zerovalent Iron (Fe^0) 5 g	94.66	---	94.66	35.88	100 min	[18]
Acid Anthraquinone Blue (AAB)	ZVI Zerovalent Iron (Fe^0)	Acid Anthraquinone Blue (AAB) 500 mg/L Zerovalent Iron (Fe^0) 5 g	89.69	---	89.69	41.2	100 min	[18]
Acid Green 25 (AG 25)	TiO2	Acid Green 80 mM 25, 2 g/L TiO2. (AG 25) pH 5.1, in aqueous solution	84.4%	50.4%	93.9%	84%	60 min	[19]
Acid Orange 7 (AO7)	TiO2	2 g of TiO2 mixed with 250 mL AO7 solution	14%	100%	---	---	30 min	[20]

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minutes with the plasma- TiO_2 system. The rate of degradation also improved markedly with the addition of TiO_2. For instance, a 1-hour plasma treatment achieved a 50% degradation rate, whereas the TiO_2-assisted system achieved 84%. The study found that 2 $g \cdot L^{-1}$ of TiO_2 was the optimal concentration for achieving the best results. Higher concentrations led to reduced efficiency due to particle aggregation and light screening effects, which prevented effective activation of the catalyst. These results, as shown in Table 3, indicate that the presence of various catalysts significantly enhances the efficiency of the gliding arc discharge plasma treatment for organic pollutant degradation. The synergistic effects of plasma-generated reactive species and photocatalytic processes are evident, providing promising and scalable solutions for industrial wastewater treatment.

These studies collectively highlight the potential of combining gliding arc discharge plasma with various catalysts for efficiently degrading organic pollutants in aqueous solutions. The synergistic effects of plasma-generated reactive species and photocatalytic processes significantly enhance degradation rates and overall treatment efficiency. This integrated method presents promising options for scalable solutions in industrial wastewater treatment. To assess the effectiveness of various treatment processes, the decolorization, degradation, and mineralization efficiencies of the selected target compounds were evaluated using specific equations. These metrics are critical for determining how well the treatments remove dyes and other organic pollutants from water.

Conclusion. The integration of gliding arc plasma technology with various catalysts presents a highly effective approach for the degradation of persistent organic pollutants in wastewater. This review has highlighted the significant advancements made in this field, demonstrating the enhanced degradation efficiencies achieved through the synergistic effects of plasma-generated reactive species and catalytic processes. Catalysts have shown remarkable potential in accelerating pollutant breakdown and improving the stability and activity of photocatalytic materials.

The studies reviewed indicate that combining gliding arc plasma with these catalysts not only increases the generation of hydroxyl radicals and other reactive species but also optimizes reaction kinetics and minimizes the formation of unwanted by-products. The effectiveness of this approach is evident in the substantial improvement in degradation rates and the overall treatment efficiency of various organic dyes and other pollutants.

However, several challenges remain, including optimizing catalyst concentrations, understanding the long-term stability of catalysts, and scaling up the technology for industrial applications. Future research should focus on addressing these challenges, exploring new catalyst materials, and developing hybrid systems that combine multiple treatment processes to enhance efficiency and sustainability. In conclusion, the plasma-catalytic approach offers a promising and scalable solution for wastewater treatment, capable of meeting the growing demand for efficient and eco-friendly pollutant degradation technologies. By continuing to refine and innovate in this area, we can make significant strides towards achieving cleaner water resources and a more sustainable environment.

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